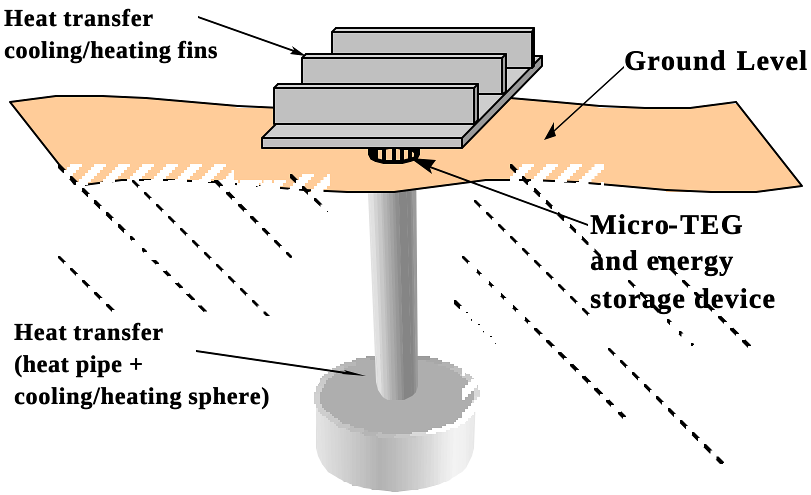
Low DT, Low Heat Flux, "Natural Heat Sources"

- Viability of using environmentally derived heat sources for powering thermoelectric generators is being evaluated
  - **Generally involve processes with DTs < 100ºC**
    - **More suited for low power applications (< 100 mW)**
- Types of heat sources that are considered include:
  - **Temperature gradients between the soil and ambient air**
  - **Heat liberated during the decomposition of organic material**
  - **Temperature gradients in liquid media**
  - **Production of biogas from the decomposition of organic material (will be used subsequently in catalytic burner)**
  - **DT's as low as 2ºC can be considered as potential heat sources**
- Key to selection process: how easily heat source can be harnessed and type of heat collection methods used
  - **Thermal processes will be assessed in terms of the energy content available for reaction with the thermoelectric converter.**

Natural Thermal Gradients

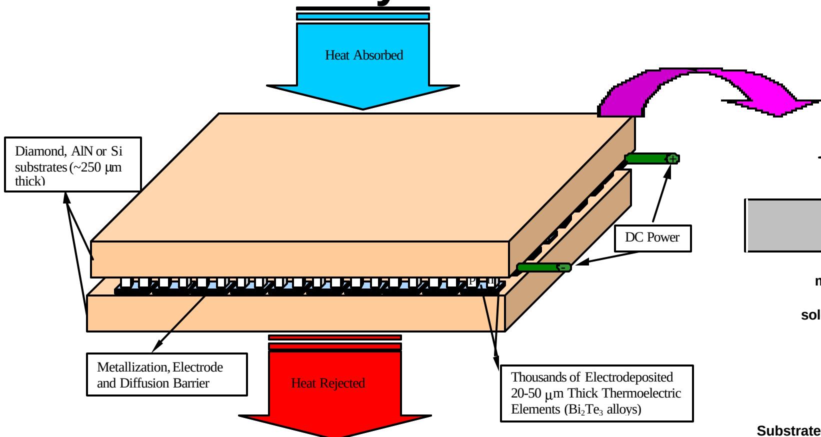
Environmental heat source development

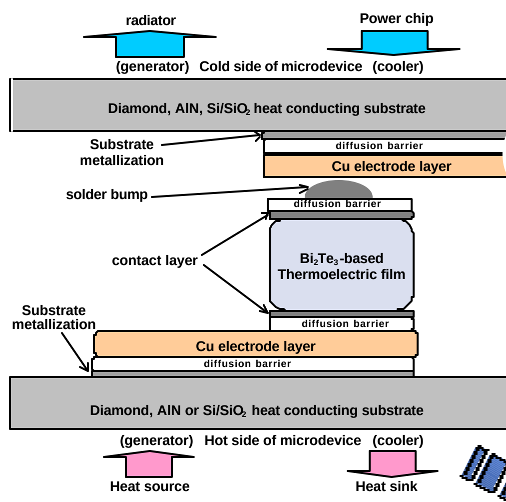
- Use of natural temperature gradients
  - **To provide 10-100s of mW output (can be as small as 1ºC).**
- One potential system involves the use of aluminum fins and heat pipes
  - **Air/soil temperature difference during day, night**
  - **Calculations show feasibility of concept for very low wind speed values (0.5 to 0.75 m/s)**
  - **Operating current and voltage can be tailored by using parallel strings of TE legs**
    - **Power conditioning**



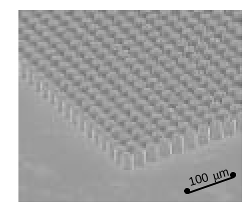
Miniaturized Thick-Film TE Converter

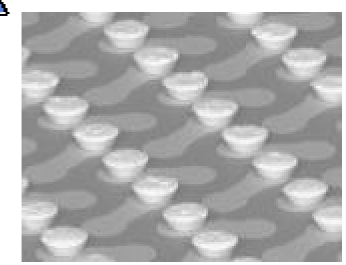
- **Objective**: Develop thermoelectric microdevices using integrated-circuit type fabrication processes, electrochemical deposition and high thermal conductivity substrates





- **Technical Approach**
  - Synthesize 5-50 mm thick films of thermoelectric materials using electrochemical deposition
  - Develop stable metallization to diamond, AlN, Si substrates
  - Develop novel techniques to fabricate microdevices

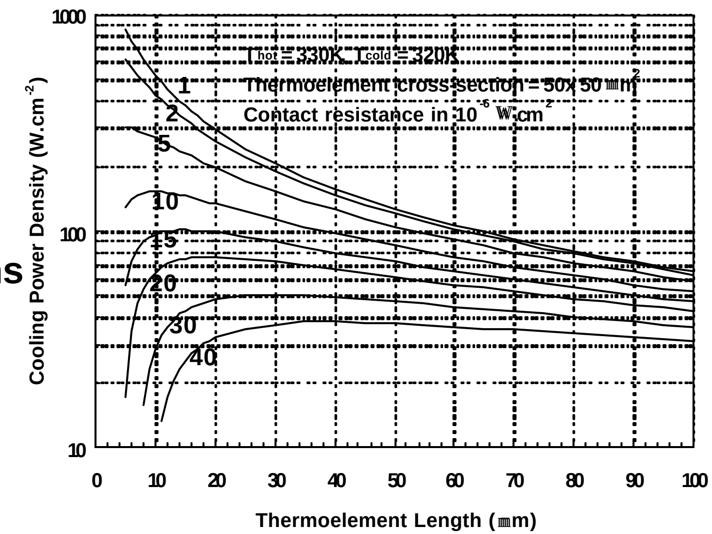


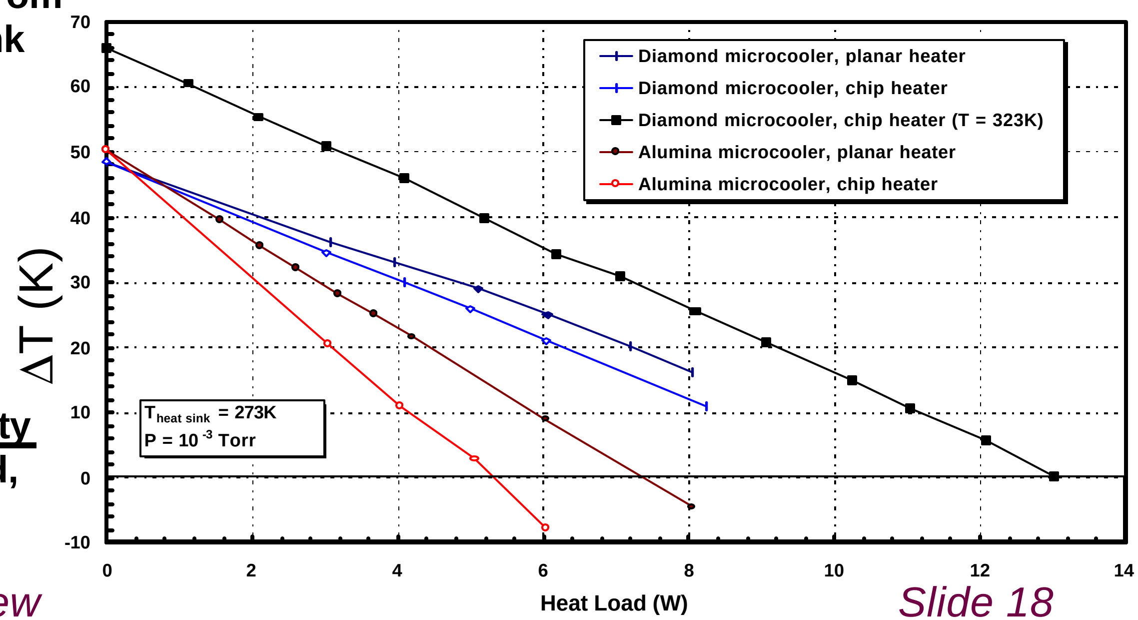


- **Design and fabrication of miniature modules**
  - Enabling technology
  - Based on thousands of micron-size thermoelectric elements
  - Challenge: device fabrication
    - Various designs depending on operating conditions (DT, Q, P_{out})
    - Performance, reliability
    - Integrate electrochemistry and electronics technology

Thermoelectric Microdevices Issues

- Miniaturized device with a classical TE module configuration
- Miniaturization issues
  - **Electrical contact resistance**
    - **More thermoelectric legs, more electrical connections**
    - **Develop <u>high quality metallization and bonding</u> schemes**
  - **Thermal resistance**
    - **Due to the ceramic substrates separating the TE material from the heat source and heat sink**
      - **Heat transfer is an important issue**
    - **Increases because the relative thickness of the substrates increases compared to the TE leg thickness**
    - **<u>Use high thermal conductivity substrates</u> such as diamond, AlN, BeO, Si/SiO_2**

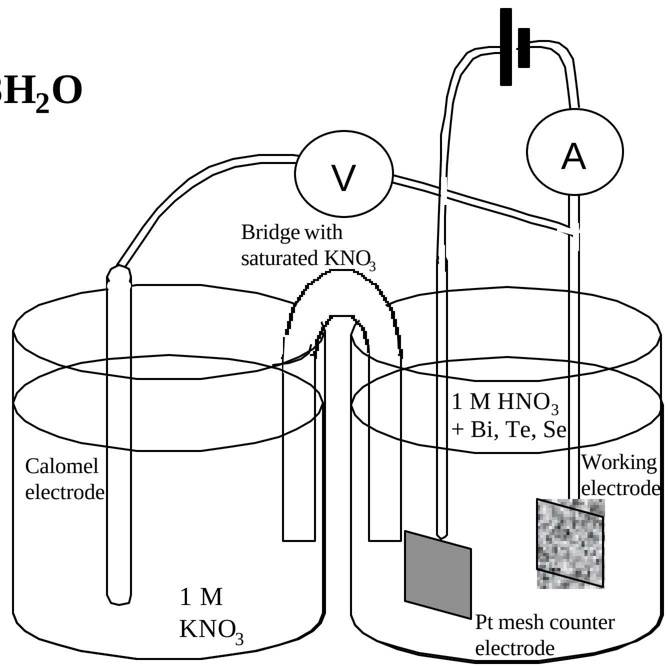




Electrochemical Deposition

- A promising route to deposition of thick films of TE materials
  - **Has been extensively used for CdSe, CdTe and alloys**
  - **Recent results on PbTe, PbSe**
  - **High deposition rate on metallic substrates**
  - **Room temperature process, inexpensive and scaleable**

- Bi_2Te_3 deposition
  - $13H^+ + 18e^- + 2BiO^+ + 3HTeO_2^+ \text{ ® } Bi_2Te_3^{\_} + 8H_2O$
  - **JPL using potentiostatic control**
    - **Manual, computer controlled-equipment**
  - **Many process parameters**
    - **Deposition voltage, deposition current [Bi] concentration, [Bi]/[Te] ratio...**
    - **Deposition setup, stirring rate, substrate quality, pH, temperature**

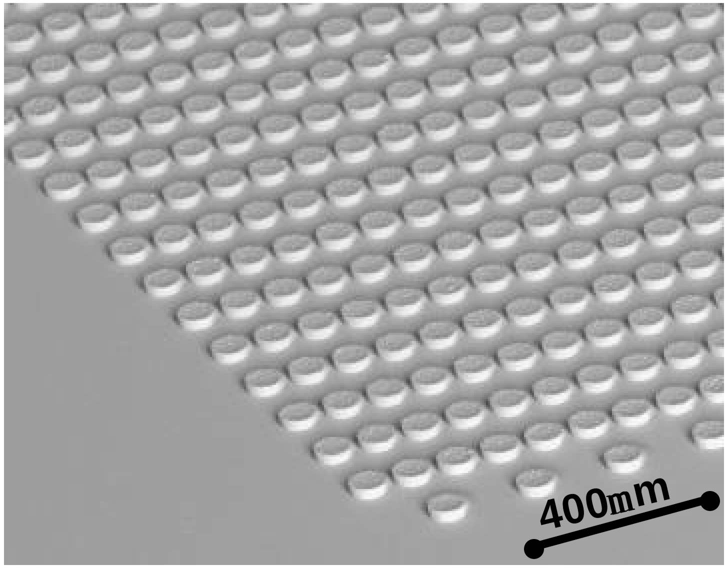


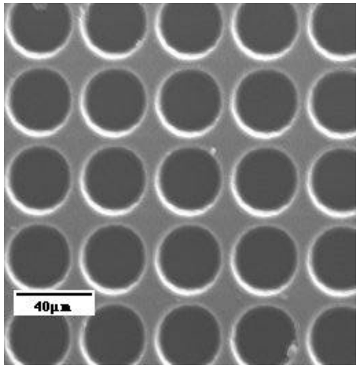
- Deposition of other metallic layers
    - **Cu, Ni, Pt, PbSn solder...**

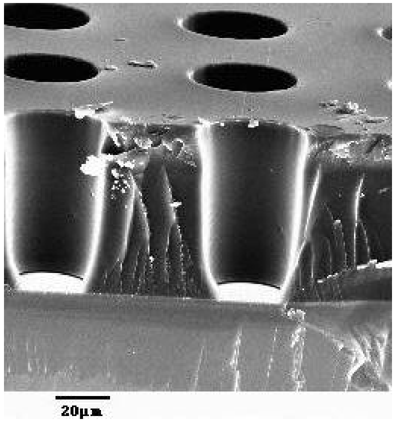
Deposition of Thermoelectric Legs

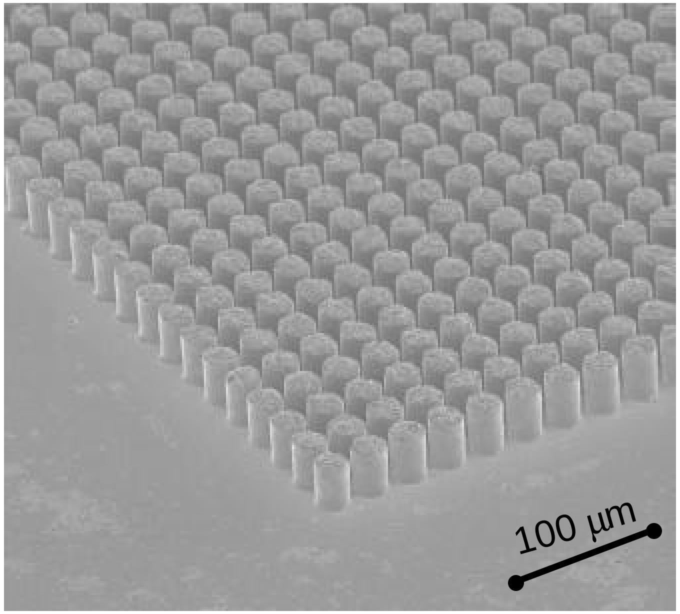
- Using patterned photoresist
  - **Team has developed thick photoresist capabilities**
    - **Up to 75 mm thick (positive PR)**
    - **Using conventional UV photolithography equipment**
- Experimental results to date
  - **Various leg geometries successfully obtained**
    - **20 mm tall, 50 mm diameter (cooling)**
    - **50 mm tall, 10 mm diameter (power generation)**
  - **Leg geometry tightly conforms to pattern geometry**
    - **Legs can be confined to patterned hole**
  - **Up to 11,000 legs grown using a 30 mm pitch**
    - **In 3x3 mm^2 area**
  - **Process offers tremendous <u>flexibility</u> for configuring microdevices**
    - **Using conventional IC-type processing**

Electrochemically Deposited Bi_2Te_3 Legs Using Thick Photoresist Templates









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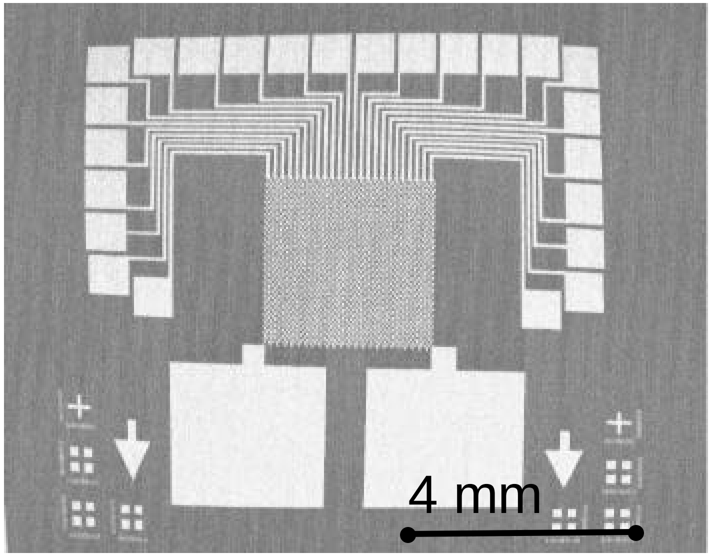
TE Microdevice Fabrication



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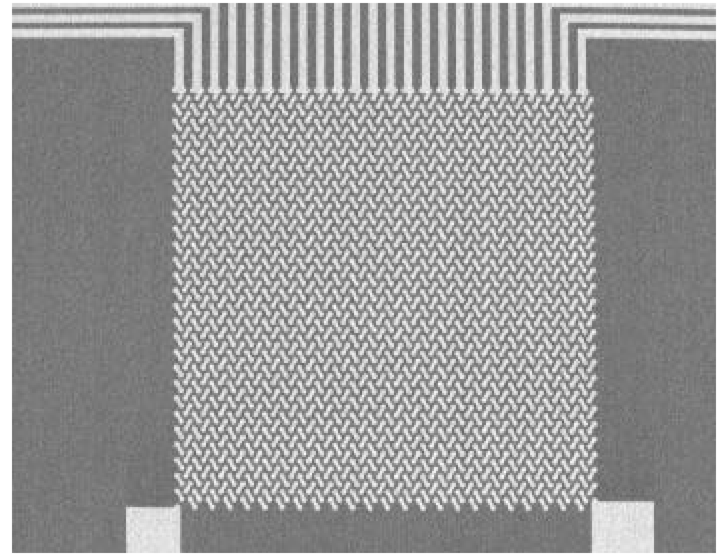

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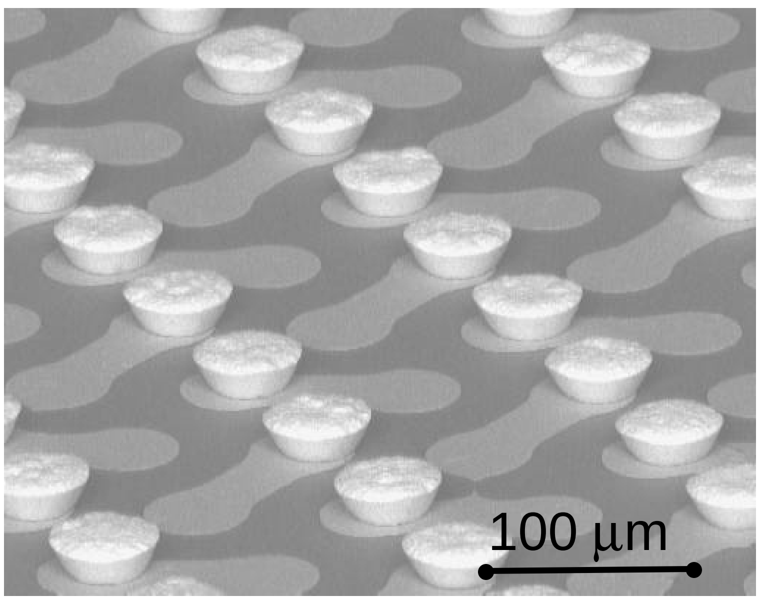

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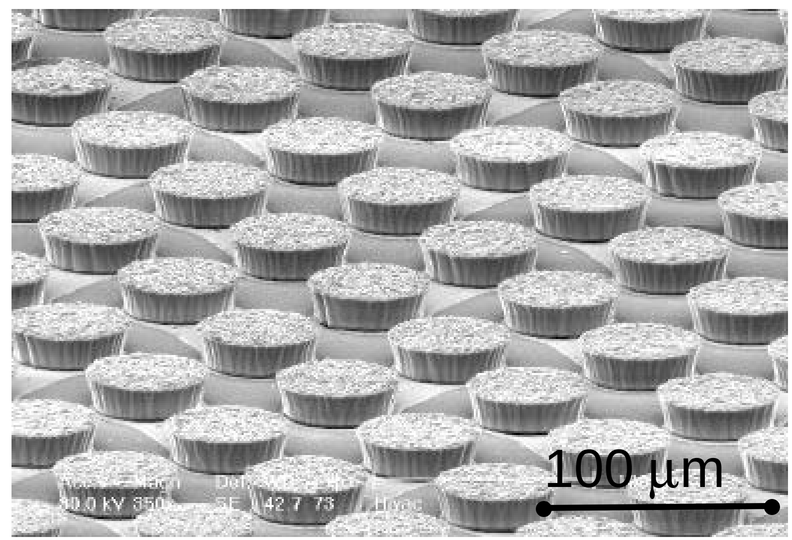

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TE Microdevice Fabrication (2)

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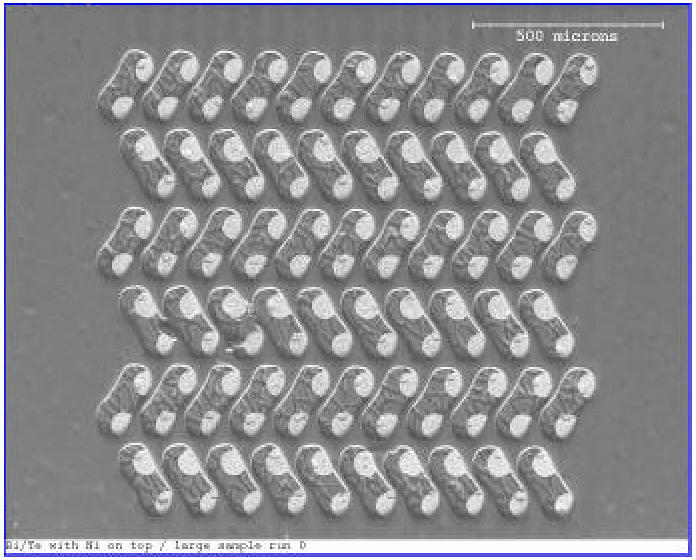

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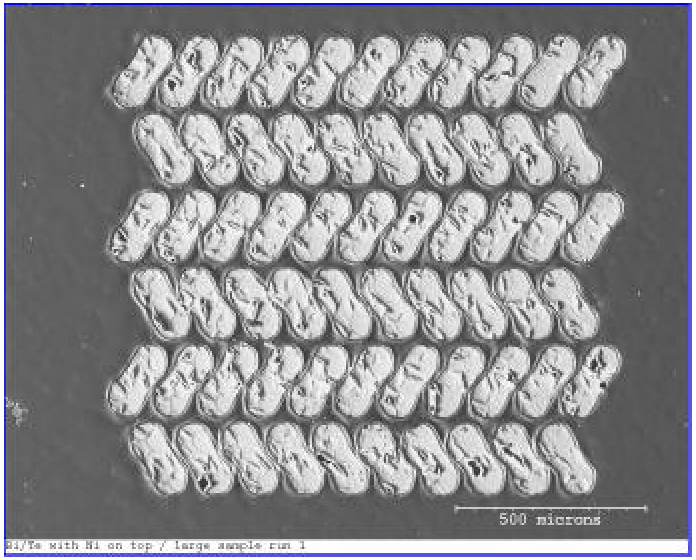

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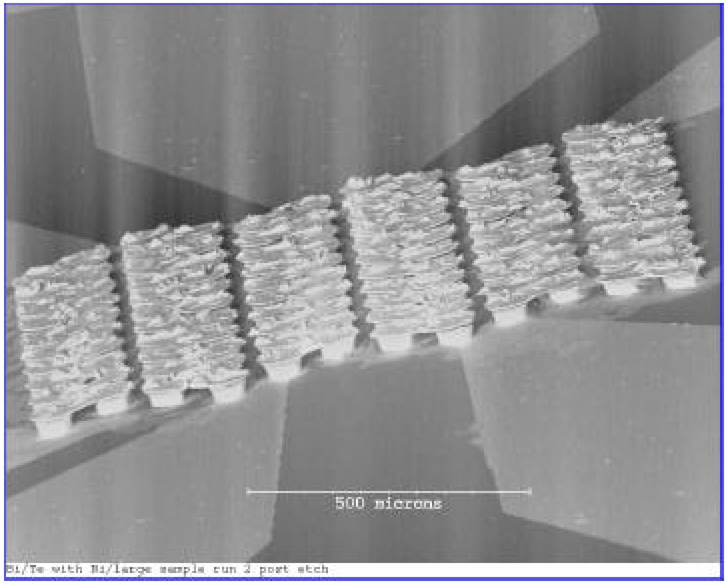

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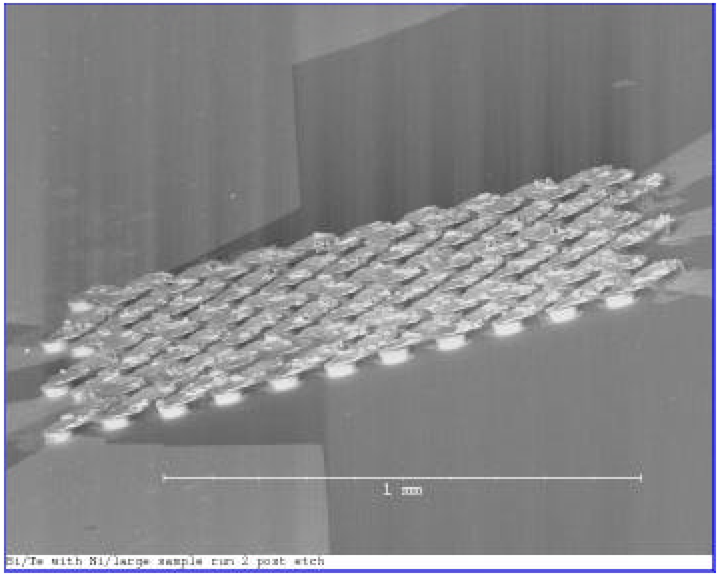

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Power Conditioning and Charge Control

Requirements

- Power Conditioning
  - **Variable power output from TE converter**
    - **Under on/off catalytic burner operation**
    - **If “natural” temperature gradient heat source**
  - **Voltage regulation required**
    - **Efficiency issues**
  - **Volume limitations**
    - **As compact and lightweight as possible**

- Charge Control
  - **Constant potential**
  - **Parasitic drain from control circuitry**
  - **Efficiency**

Power Conditioning and Charge Control

- Approach
  - **Integrate JPL system components for 100mW and 5W power source devices.**
  - **Test integrated 100mW and 5W power sources to remote sensor specifications.**
  - **Evaluate charge control design for button cells using charge/discharge interrupt devices for efficiency and temperature performance.**
  - **Conduct long term float charge characterization of button cell and D-sized lithium ion cells.**
  - **Characterize cell performance over temperature range.**

- Accomplishments to date:
  - **Surveyed commercial charge control circuits for lithium ion batteries.**
  - **Evaluated charge control circuits for D-sized lithium ion cells.**
  - **Identified sources for lithium ion cells and charge control circuits for 100mW and 5W power systems.**

Status

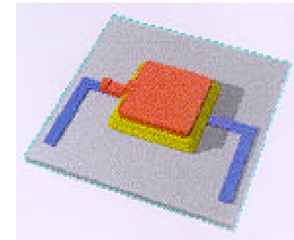
- Accomplishments to date:
  - **Tools for flexible thermal/electrical analysis developed**
    - **Now focusing on full designs for various device configurations**
    - **Heat generation, heat transfer and power generation models integrated**
  - **Technology for TE micodevice fabrication demonstrated**
    - **Leveraged by other JPL programs focusing on basic scientific and technical issues related to cooling applications and very low power devices (μW)**
    - **Now testing feasibility of all fabrication steps**
    - **First full prototype fabricated**
      - **Based on a combination of electrochemistry and IC processing techniques**
  - **Initial study of miniature catalytic burners completed**
    - **Defined burner design characteristics for integration with micro-TEG**
    - **Set up test stand for evaluation of performance of catalytic heaters**
    - **Demonstrated steady-state operation**
      - **With suitable physical footprint, temperature and heat flux characteristics**
  - **Preliminary work on power conditioning/charge control completed**
    - **Rechargeable Li-ion battery sizing**
      - **Based on state-of-the-art available technology and for various duty cycles**
    - **Parts for electronics being procured**

Plans for Remainder of Program

- Heat source
  - Complete catalytic burner development and characterization
    - Evaluate supported platinum catalysts and zirconia and silica wicks/substrates.
    - Examine other liquid fuels such as ethanol and higher hydrocarbons
    - Investigate and test integrated architectures for burner and heat collection
    - Determine 3-dimensional design for optimal air utilization in the catalyst layer.
- TEMG
  - Procure, test small bulk thermopiles adapted to high heat fluxes
    - 10-20W/cm^2
  - Fully operational prototype microdevices to be fabricated and tested by end of FY00
    - With complete source integration in FY01
- Li-ion rechargeable batteries
  - Design study, selection and testing of state-of-the-art technology
  - Evaluation of advanced solid electrolyte Li-ion technology for integration
- Power conditioning and system integration
  - Design, develop and test power conditioning electronics
  - Test micro-TEGs coupled to selected heat source technologies
  - Integrate and test complete prototype power package

TEMGs: Future directions

- High efficiency, long life, ultra compact power sources
- Integration with System On A Chip program (JPL-CISM)
  - **On-chip power sources (mWs to mW per mm^3 range)**
    - **ARPS: use of advanced radioisotope heat sources**
      - **500-800 mm small particles nuclear fuel ("Paintable" heater)**
    - **Possibly combined a -voltaics/thermoelectrics**
    - **Use of energy harvesting schemes ("power skin")**
- Develop further current IC-ECD techniques for SOAC
  - **New materials, structures and device concepts**
    - **Low-dimensional effects on electrons and phonons have the potential to significantly increase the ZT, conversion efficiency**
  - **Use of high energy density fuels**
    - **Potential for very high electrical power output densities**
  - **Use advanced MEMS-type processing techniques**
    - **Electrochemical fabrication**



On-Chip Power Source